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Analysis of an Autostereoscopic Display: The Perceptual Range of the Three Dimensional Visual Fields and Saliency of Static Depth Cues

Paul R. Havig
John P. McIntire

Human Effectiveness Directorate
Warfighter Interface Division
Wright-Patterson AFB OH 45433-7022

Rhoshondra A. McGruder

United States Air Force Academy
Colorado Springs CO

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Human Effectiveness Directorate
Warfighter Interface Division
Wright-Patterson AFB OH 45433

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Paul Havig[a], John McIntire[b], Rhoshonda McGruder[c]
[a]Air Force Research Laboratory AFRL/HECV, 2255 H. St., Wright-Patterson AFB OH, USA 45433
[b] Consortium Research Fellows Program, Arlington, VA
[c] United States Air Force Academy, USAFA, CO

ABSTRACT

Autostereoscopic displays offer users the unique ability to view 3-dimensional (3D) imagery without special eyewear or headgear. However, the users' head must be within limited "eye boxes" or "viewing zones." Little research has evaluated these viewing zones from a human-in-the-loop, subjective perspective. In the first study, twelve participants evaluated the quality and amount of perceived 3D images. We manipulated distance from observer, viewing angle, and stimuli to characterize the perceptual viewing zones. The data was correlated with objective measures to investigate the amount of concurrence between the objective and subjective measures. In a second study we investigated the benefit of generating stimuli that take advantage of monocular depth cues. The purpose of this study was to determine if one could develop optimal stimuli that would give rise to the greatest 3D effect with off-axis viewing angles. Twelve participants evaluated the quality of depth perception of various stimuli each made up of one monocular depth cue (i.e., linear perspective, occlusion, haze, size, texture, and horizon). Viewing zone analysis is discussed in terms of optimal viewing distances and viewing angles. Stimuli properties are discussed in terms of image complexity and depth cues present.

Keywords: viewing zone, 3D, autostereoscopic, depth cue, display

1. INTRODUCTION

Increasing advances in display technology offer a multitude of new and innovative visualization tools. Much excitement is centering on 3-dimensional (3D) displays that only recently have become practical to build and use. Because human depth perception relies on binocular vision, most 3D displays project separate images to each eye, creating unique human factors issues not typically seen in traditional 2D displays. Most commonly, binocular displays require that users wear special eye-glasses or don headgear (e.g., a helmet-mounted display) to ensure different images are projected to one and only one eye.

Autostereoscopic displays offer users the ability to view 3-D imagery without special eyewear or bulky headgear. However, this type of display restricts users' head movements within limited perceptual fields called "eye boxes" or "viewing zones." While some studies have included the objectively-measured or mathematically-derived parameters of 3D visual fields[1-3], no one seems to have analyzed the situation from a human-in-the-loop, subjective perspective.

Some researchers[3] have calculated the sizes and shapes of the 3D viewing zones of autostereoscopic displays based solely upon the physical parameters of the display. Others[1] mathematically modeled and then measured the intensity fluctuations of a flat-panel autostereoscopic display as the screen was moved laterally. They found that lateral movements of a rear parallax barrier display of 1 to 2 mm caused an intensity change of 1%, an amount that is theoretically detectable by an observer. These movements correspond to screen rotations of approximately 0.1 to 0.2 degrees. The calculations suggest that autostereoscopic displays have relatively small viewing windows, on the order of a few degrees, with little tolerance for off-axis rotation or movement outside of the eye box.

In a study using an autostereoscopic display for teleoperations[4], improved performance was found when using an autostereoscopic display to remotely operate an underwater vehicle when compared to a traditional 2D display. However, subjective evaluations from users cited the severe limitations on lateral head movement. The research suggested that the restriction on lateral movement is the major shortcoming preventing user acceptance and widespread use of autostereoscopic technology.

The present studies investigate the physical and perceptual characteristics of the 3D viewing zones on a parallax barrier autostereoscopic display. Off-axis perceptibility of various images is tested at different distances. The saliency of several static monocular depth cues is also analyzed to investigate off-axis perceptibility. Viewing zone analysis is discussed in terms of optimal viewing distances and viewing angles. Stimuli properties are discussed in terms of image complexity and depth cues present. Recommendations on stereoscopic display properties, image properties, and applications are made accordingly.

2. EXPERIMENT 1

2.1. Method

There were two main objectives to this experiment. First, we wished to better understand the perceived amount and quality of a 3D stimulus as it was rotated about the center axis. Off-axis viewing leads to a change in the eye box and we wished to see how that affected observers' ability to see 3D. Second, we wanted to see how much of an effect there would be using non-optimal viewing distances (i.e., not the manufacturer's recommended viewing distance). We did this by using the recommended distance (23 inches) and two non-optimal distances (17 and 29 inches).

2.2. Participants

Twelve volunteers participated in the experiment, the three authors and nine others who where naïve as to the purpose of the study. All observers had normal or corrected-to-normal visual acuity and normal color vision, as indicated by the Ishihara pseudo-isochromatic plates and the Farnsworth F_2 Tritan plate. All observers tested normal on the TNO test for stereoscopic vision.

2.3. Apparatus and Stimuli

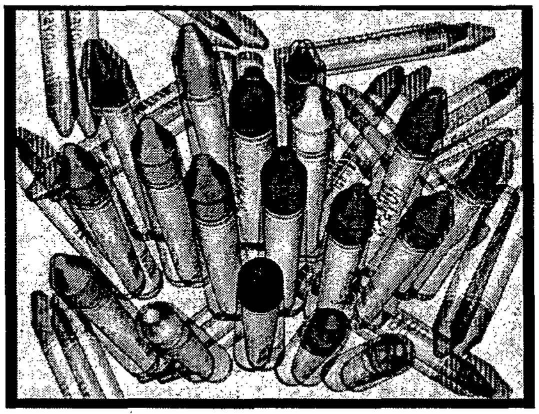
The display used a Sharp Actius RD3D autostereoscopic notebook computer. The RD3D has a screen size of 15.0 inches (diagonal) and a resolution of 1024 x 768 pixels (XGA).

The stimuli were five stereoscopic images of various types as shown in Figure 1. We chose the stimuli to give a range of complexity as well as different types of images. As seen in Figure 1, two were created from photographs (one from the Sharp demo and one we created), two others were created by ourselves using a modeling program (Blender), and the last was also in the Sharp demo. Note that we show the actual stimuli (hence the double images in Figure 1).

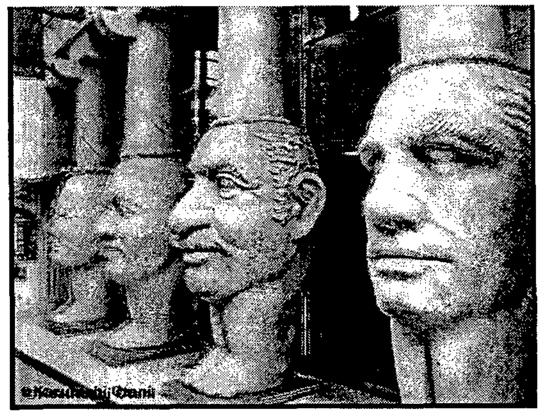
2.4. Procedure

Observers sat at the end of a table and faced the display. A chinrest mounted on the end of the table was used to keep the observer at the correct distance for each trial and centered their line of sight with the center of the display. On the table sat a movable display mount that allowed the experimenter to slide the display toward and away from the observer at set distances. The display was also mounted on a motorized rotational platform which allowed the experimenter to manipulate the off-axis viewing angles.

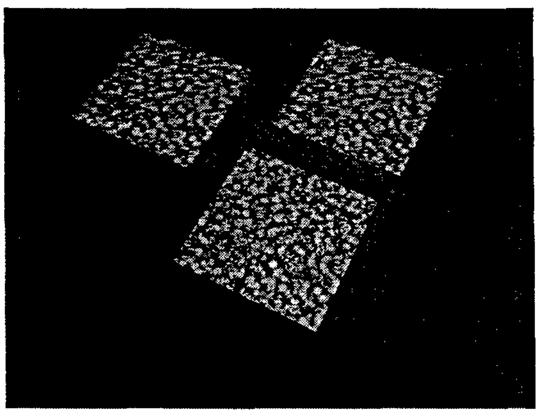
Observers were instructed that they would be asked to give their judgments on three questions: 1) whether any 3D is perceived in the image, 2) the amount of the stimuli that appears 3D (0 – 100), and 3) the quality of the 3D that is



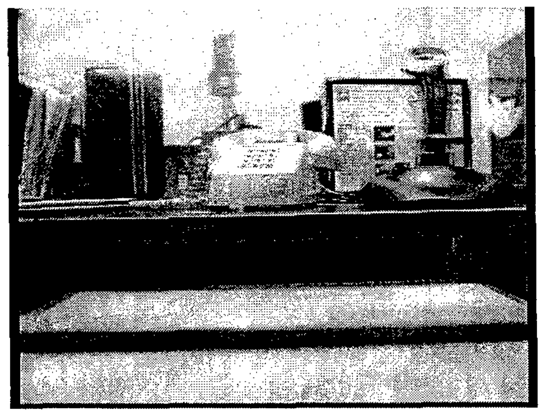
Crayons



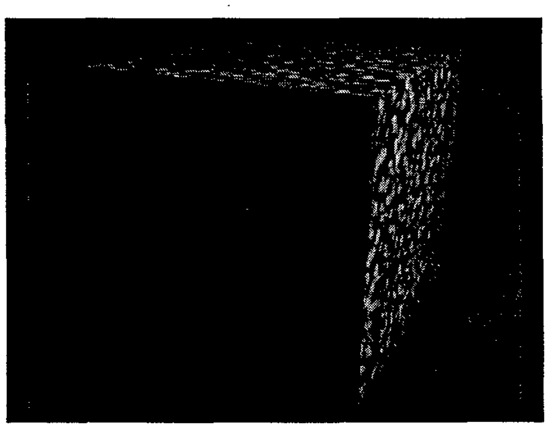
Head Feet



Three Cubes



Telephone



Big Cube

Figure 1. Stimuli for Experiment 1

present (1 very poor – 5 very good). Starting at zero degrees, observers gave responses for all five images at 13 different degrees of rotation (0 through 12) and at three different distances (17, 23, and 29 inches). The order in which observers viewed the distances was randomized and balanced. Responses were recorded by the experimenter. There were three experimental sessions for each participant, one for each distance. Each session lasted no more than an hour, so each observer participated for 3 hours at most, spread over several days.

2.5. Results

Two separate analyses were performed on the data. First, a full factorial analysis of variance (ANOVA) was conducted on the perceived amount of 3D data using distance from observer, rotation in degrees, stimulus, and 3D present/absent as the main effects. The analysis revealed significant main effects of distance from observer $F(2,2048) = 4.12$, $p = .0164$, rotation in degrees $F(12,2048) = 2.15$, $p = .0119$, 3D present/absent $F(1,2048) = 246.24$, $p < .0001$, and the interaction of distance from observer by rotation in degrees $F(24,2048) = 5.13$, $p < .0001$. The main effect of stimulus and all other interactions were nonsignificant at the .05 level. The interaction of distance from observer and rotation in degrees is shown in Figure 2.

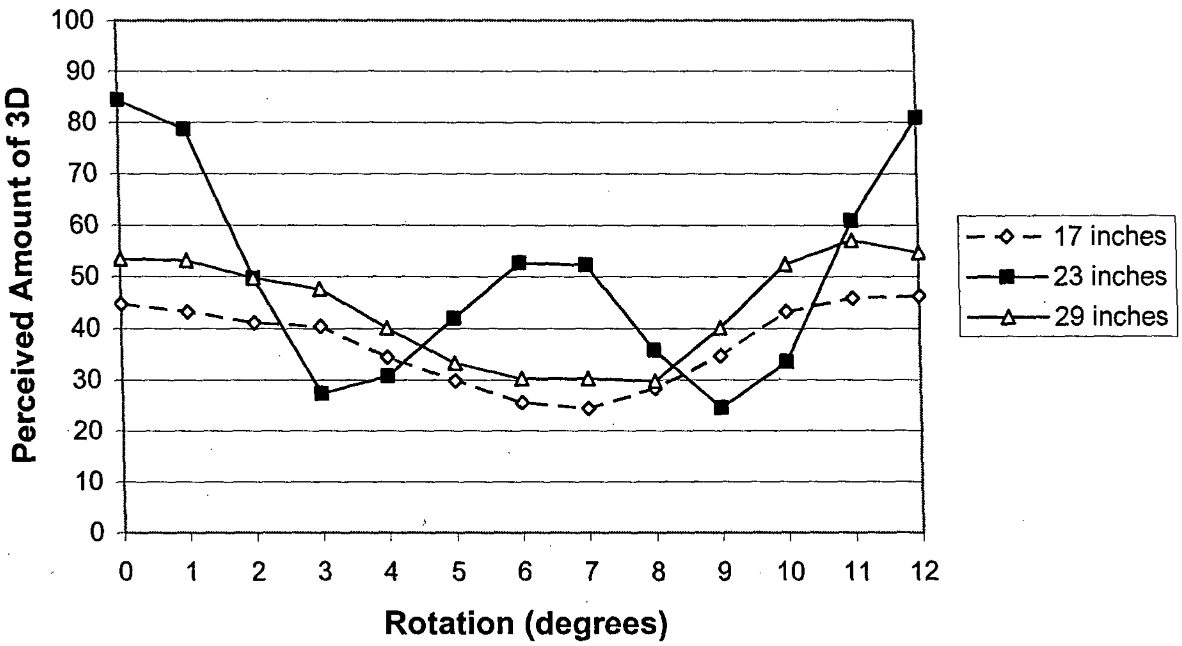


Figure 2. Perceived Amount of 3D as a Function of Degree of Rotation and Distance from Observer

For the second analysis an ANOVA was conducted on the perceived quality of 3D data again using distance from observer, rotation in degrees, stimulus, and 3D present/absent as the main effects. The analysis revealed significant main effects of stimulus $F(4, 2048) = 11.44$, $p < .0001$, distance from observer $F(2,2048) = 3.51$, $p = .0301$, rotation in degrees $F(12,2048) = 2.88$, $p = .0006$, 3D present/absent $F(1,2048) = 55.18$, $p < .0001$, and the interaction of distance from observer by rotation in degrees $F(24,2048) = 6.35$, $p < .0001$. All other interactions were nonsignificant at the .05 level. A post hoc analysis on stimulus using Tukey's HSD test at the .05 alpha level revealed no significant differences between the stimuli (Telephone, Head Feet, and Three Cubes) but these three were all significantly different from Crayons and Big Cube, both of which were significantly different from each other. The main effect of stimuli is shown in Figure 3 with the post hoc analysis indicated by connecting lines (bars connected by lines are not significantly different). The interaction of distance from observer and rotation in degrees is shown in Figure 4.

2.6. Discussion

As shown in Figure 2, there was a significant interaction of rotation in degrees and viewing distance on observers' perceived amount of 3D present in the stimuli. The optimal viewing distance (23 inches) is different from the two non-optimal distances (17 and 29 inches) showing more off-axis points in which observers report a larger amount of 3D. As a quick check of these results we performed our own objective analysis in which we made a full-screen red field and a full-screen blue field which we then used as left and right images. This did not generate a 3D view but did allow us to take spectraradiometric measurements as we rotated the display about the center axis. We then took the baseline blue chromaticity measurement and the chromaticity measurements for each off-axis measurement and calculated the Euclidian distance between the two. These results are shown in Figure 5.

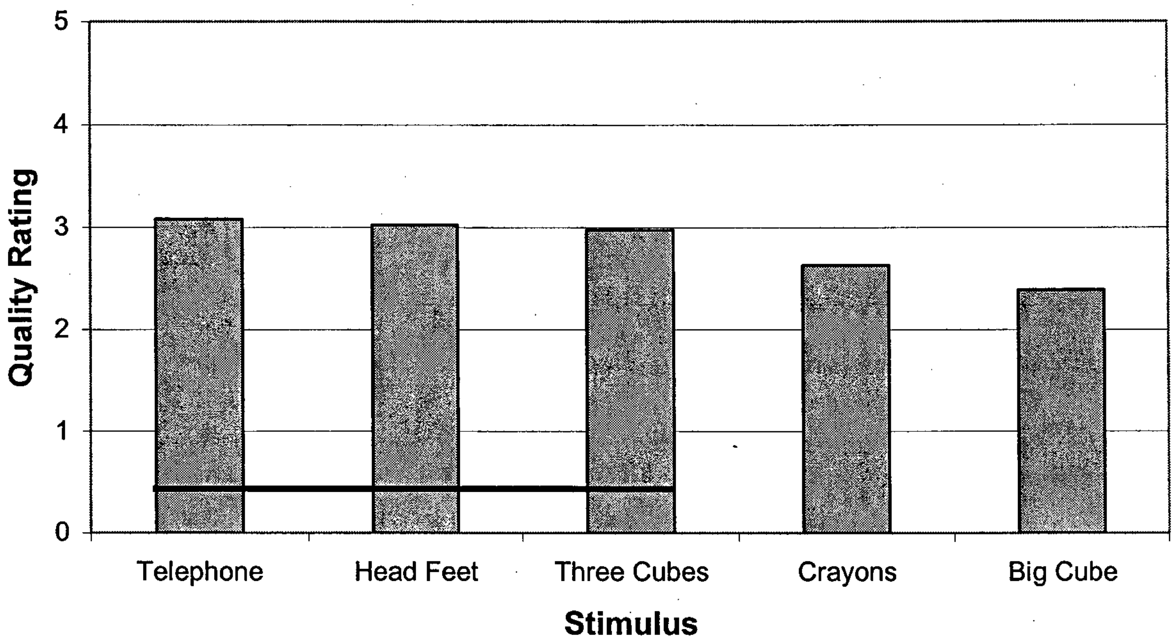


Figure 3. Perceived Quality of 3D as a Function of Stimulus

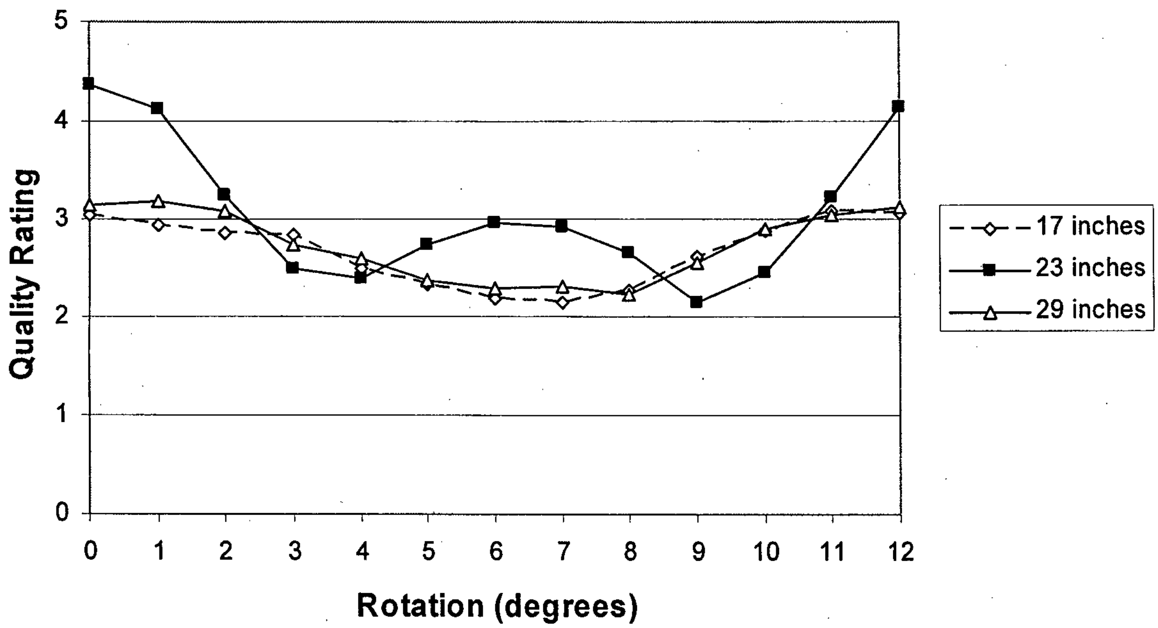


Figure 4. Perceived Quality of 3D as a Function of Degree of Rotation and Distance from Observer

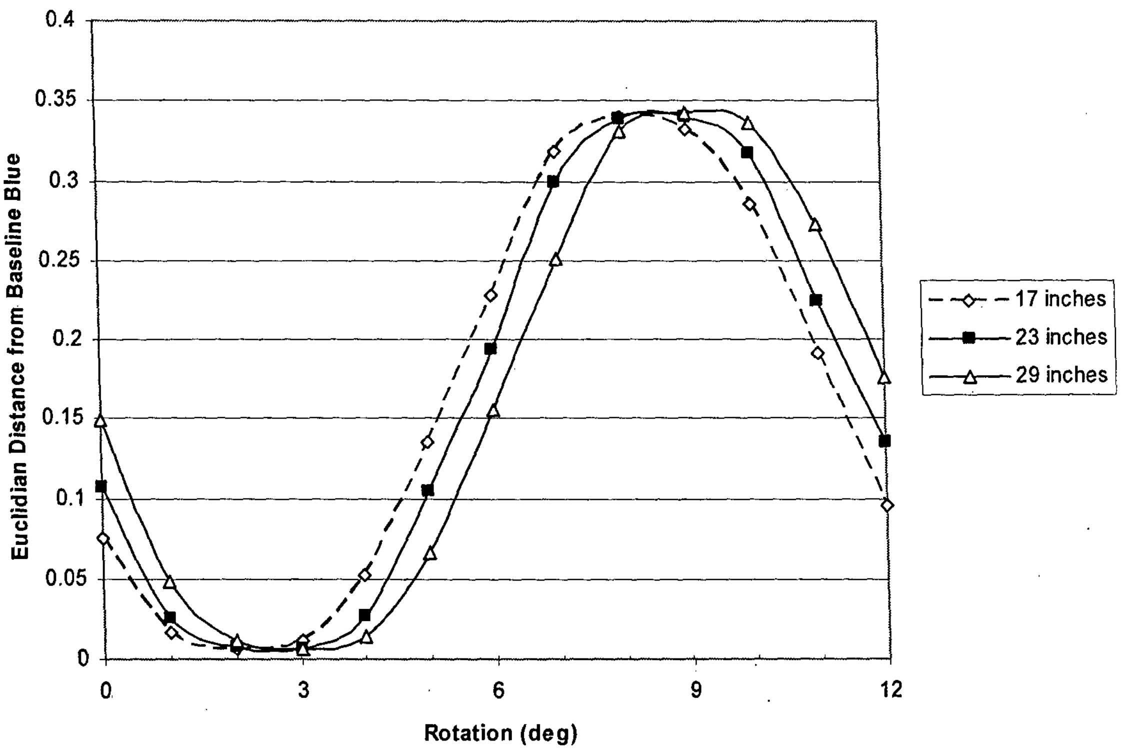


Figure 5. Objective Difference Metric

There are several interesting things to note here. First, the two non-optimal distances flank the optimal showing the color shift that occurs at the various distances. Second, one can see that the 0 degree measurements are seen roughly again at 5 degrees and 12 degrees. If one compares Figure 2 and Figure 5 there is a striking correlation between the objective and subjective measures showing that observers' subjective metrics correlated with some simple objective metrics. Moreover, the "hump" in the middle of the data that is at the 5 – 7 degree point and the 12 degree marks are roughly the same for both objective and subjective measures.

As for the perceived quality of 3D we note in Figure 3 a significant difference between stimuli. We are not sure of the exact reason for this effect and attempted to investigate it further in the second experiment. However, looking at the stimuli in Figure 1, there may be an effect of the amount of disparity in each image which may account for certain stimuli being seen as better. Further, in Figure 4 we note similar results to Figure 2 showing observers were able to make replicable subjective metrics for both perceived amount and quality of 3D.

We can conclude from this first experiment that both the perceived amount and perceived quality of 3D drops off rapidly when viewed from off-axis angles. In fact a shift of only 1 – 2 degrees causes a marked decrease in quantity and quality (see Figures 2 and 4). However, quality seemed to be dependent upon the stimulus. We found a significant difference between the stimuli which upon their review we were unable to explain. We attempted to investigate this further in the second experiment.

3. EXPERIMENT 2

3.1. Method

The purpose of this experiment was to investigate the effects of image properties upon 3D perception in off-axis viewing conditions. In Experiment 1, we found differences between the perceived 3D of the different images, which we believed were potentially due to the monocular depth cues present in the images. Monocular depth cues are unique types of visual information that allow depth and spatial information to be extracted from a scene; they are only two dimensional and do not require binocular vision to be perceived. Despite being commonly confined to a 2D canvas or photograph, artists and photographers commonly use monocular cues to create a sense of depth, such as capturing a distant landscape that becomes hazy as it recedes, or viewing railroad tracks that converge at the horizon.

When viewing 3D stimuli on a 3D display, binocular depth cues are always present. However, different monocular depth cues can be present or absent to varying degrees. To test how monocular depth cues affect the perception of 3D, particularly in off-axis viewing conditions, six unique stimuli were created. Each emphasized a particular static, monocular depth cue: linear perspective, texture, haze, occlusion, relative size, or relative height to the horizon.

3.2. Participants

Twelve volunteers participated in the experiment, two of the authors and ten others who where naïve as to the purpose of the study. Again, all observers had normal or corrected-to-normal visual acuity, normal color vision, and normal stereoscopic vision.

3.3. Apparatus and Stimuli

The display used was the same as in Experiment 1, and the stimuli were six stereoscopic images of various types that emphasized different static, monocular depth cues as shown in Figure 6.

3.4. Procedure

Similar to Experiment 1, observers sat at the end of a table and faced the display. A chinrest mounted on the end of the table was used to keep the observers centered. As in Experiment 1, the motorized platform allowed the experimenter to manipulate the off-axis viewing angles.

Observers were instructed to give their judgments on only two questions: 1) the amount of the stimuli that appears 3D (0 – 100) and 2) the quality of the 3D that is present (1 very poor – 5 very good). Starting at zero degrees, observers gave responses for all six images at 13 different degrees of rotation (0 through 12). The order in which observers viewed the images was randomized and balanced. Responses were recorded by the experimenter. There was only one experimental session for each participant which lasted no more than an hour.

3.5. Results

Again, two separate analyses were performed on the data. First, a full factorial ANOVA was conducted on the perceived amount of 3D data using rotation in degrees and stimulus as the main effects. The analysis revealed significant main effects of stimulus $F(5,858) = 21.7, p < .0001$ as well as rotation in degrees $F(12,858) = 29.96, p < .0001$. However, the interaction of stimulus and rotation in degrees was nonsignificant at the .05 level. A post hoc analysis on stimulus using Tukey's HSD test at the .05 alpha level revealed no significant differences between the following groups of stimuli (linear, haze, and size), (size and texture) and (texture, horizon, and occlusion). These results are shown in Figures 7 and 8. Note in Figure 7 that bars connected by a line are not significantly different from each other.

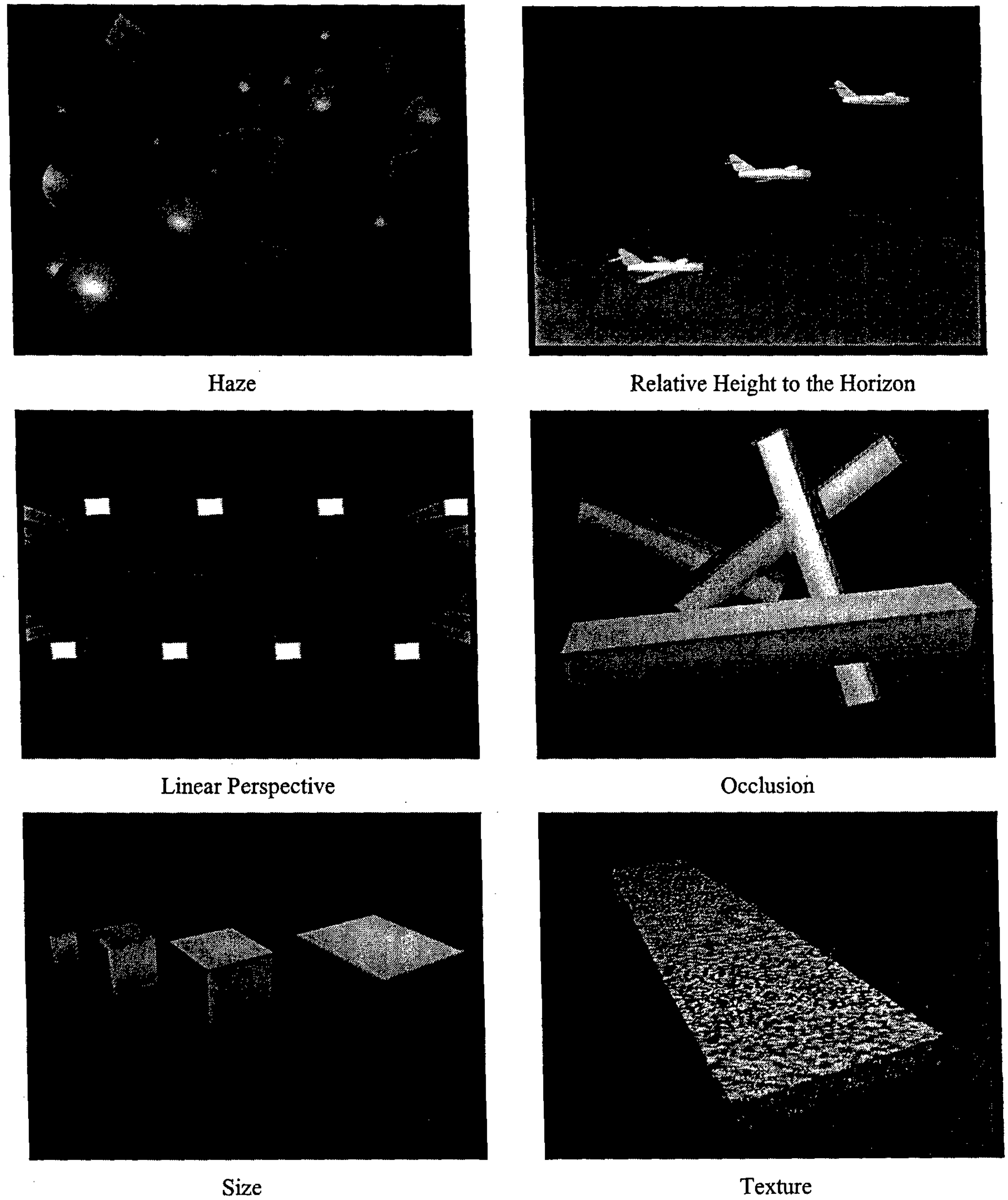


Figure 6. Stimuli for Experiment 2

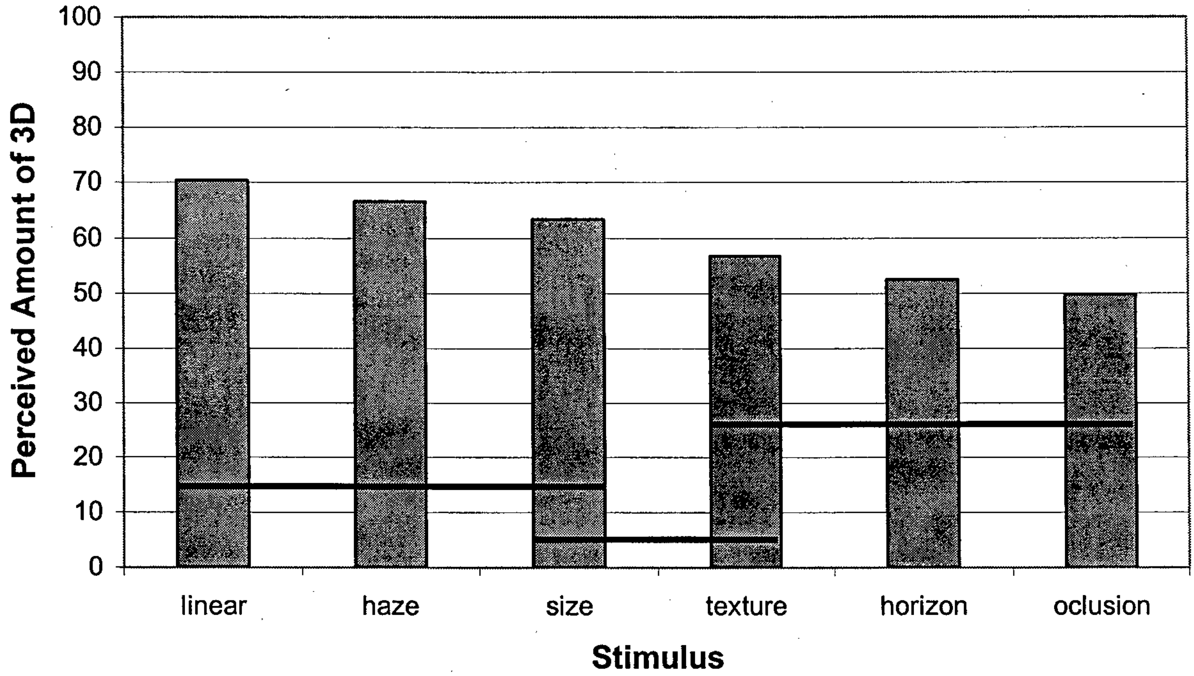


Figure 7. Perceived Amount of 3D as a Function of Stimulus

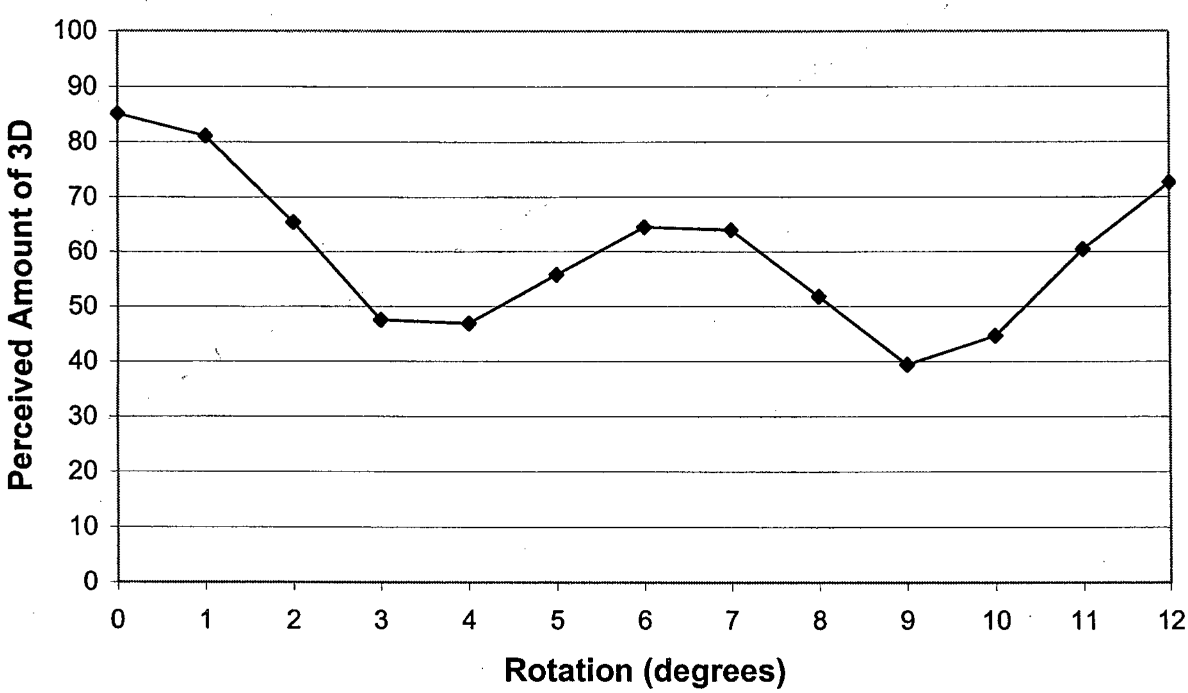


Figure 8. Perceived Amount of 3D as a Function of Rotation in Degrees

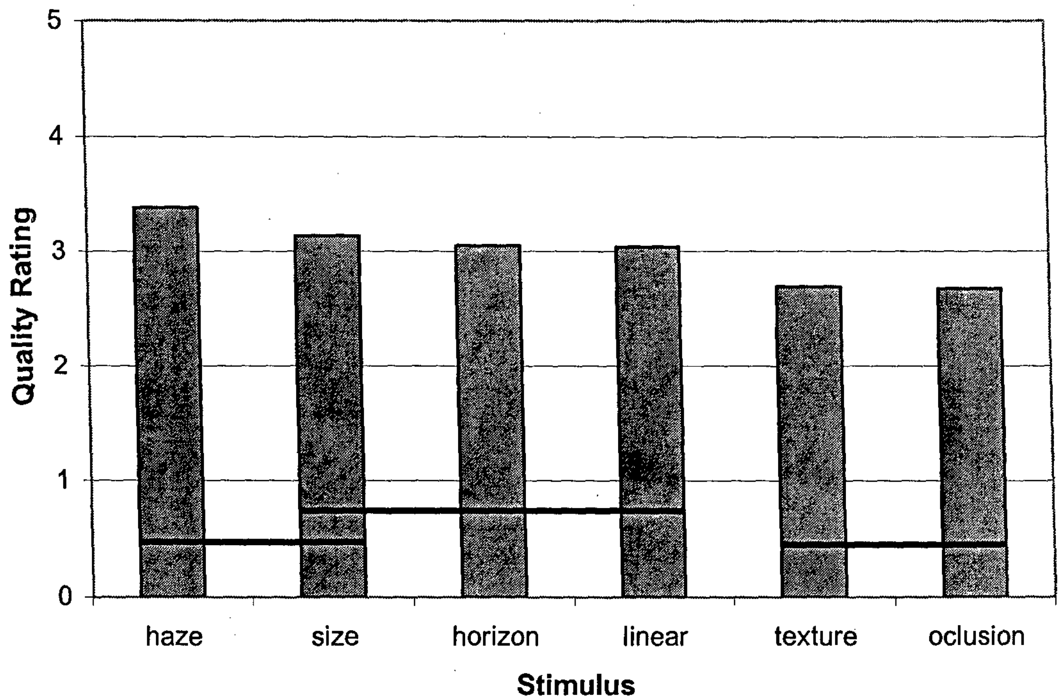


Figure 9. Perceived Quality of 3D as a Function of Stimulus

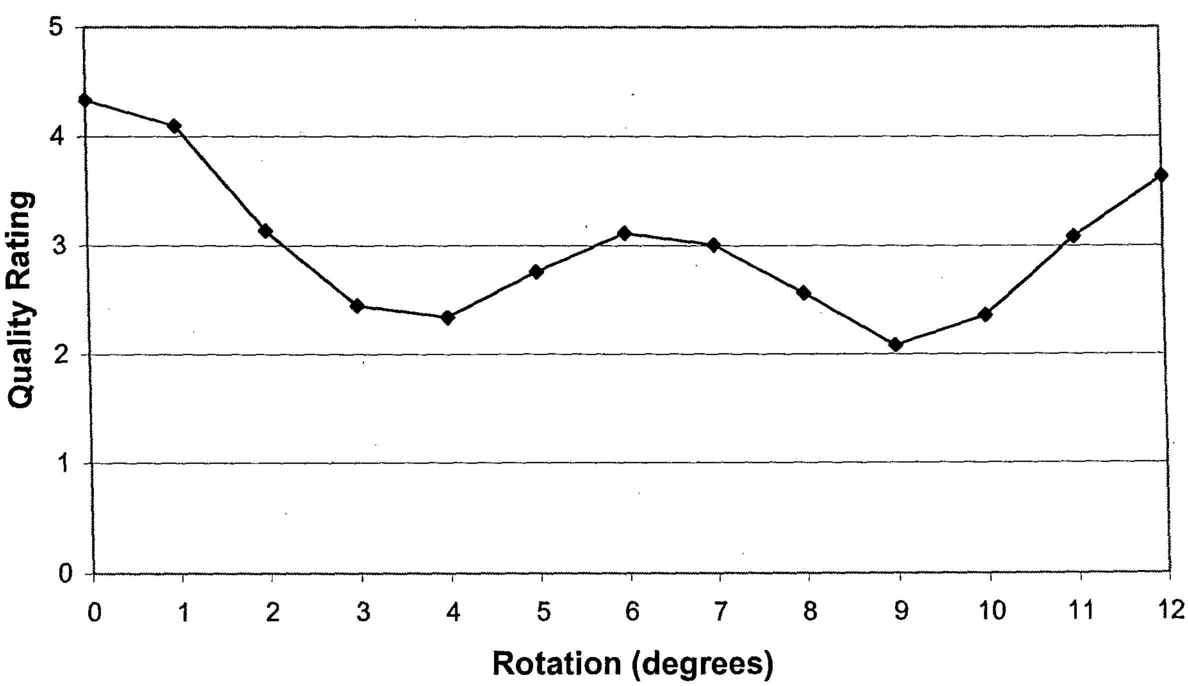


Figure 10. Perceived Quality of 3D as a Function of Rotation in Degrees

For the second analysis an ANOVA was again conducted on the perceived quality of 3D data again using stimulus and rotation in degrees as the main effects. The analysis revealed significant main effects of stimulus $F(5,858) = 15.62$, $p < .0001$ as well as rotation in degrees $F(12,858) = 46.3$, $p < .0001$. However, the interaction of stimulus and rotation in degrees was nonsignificant at the .05 level. A post hoc analysis on stimulus using Tukey's HSD test at the .05 alpha level revealed no significant differences between the following groups of stimuli (haze and size), (size, horizon, and linear) and (linear, texture, and occlusion). These results are shown in Figure 9 and 10. Note in Figure 9 that bars connected by a line are not significantly different from each other.

3.6. Discussion

In the second experiment we attempted to see if taking advantage of individual monocular depth cues would help to "expand" the eye box. In this experiment we found a significant main effect of stimulus for perceived amount of 3D as shown in Figure 7. As can be seen linear perspective gave rise to the greatest average perceived amount of 3D with occlusion perhaps surprisingly the least. However, upon review we found that we still have confounds in that each of the stimuli were not equally complex nor were they each perfectly free of other depth cues. As in the first experiment, we did find a significant main effect of stimuli for perceived quality of 3D. However, if one compares Figures 7 and 9 there is not a good correlation between perceived amount and perceived quality of 3D.

A further finding was our replication of results from the first experiment in that for both perceived amount and perceived quality of 3D we found the same trend as before as shown in Figures 8 and 10. This trend follows the objective measurements as in the first experiment and shows that overall observers were able to give reliable and consistent subjective ratings.

CONCLUSIONS AND FUTURE RESEARCH

The purpose of the present experiments was to determine how well the quantity and quality of the 3D image is as the stimulus is viewed off-axis or at a non-optimal viewing distance. The issue arises as there are very few instances in which someone would use one of these displays as done here (i.e., in a controlled laboratory setting with a chin rest). In reality, viewers move in and out and back and forth while looking at a display. Here we attempted to see subjectively how well the 3D percept holds as it is viewed in non-optimal conditions.

In the first experiment we used five stimuli of differing complexity, had observers view them at three distances, and at 13 different off-axis degrees. Observers made judgments of the amount of 3D present as well as its quality. We found that at the optimal distance observers perceived the quantity and quality of 3D to be better than at the non-optimal distances. Likewise both quantity and quality varied as a function of rotation in degrees. Interestingly, we found a rough similarity between our own objective measure and observer's subjective ratings showing that they were able to perform the task and consistently rate the stimuli. Finally we found for observer's rating of quality there was a significant effect of the stimulus but do not have a good explanation of why those results arose.

Our second experiment was developed to look at two specific issues: 1) why was there an effect of stimulus and 2) is there a way to make an "optimal" stimulus. To do this we used six stimuli that we developed to take advantage of one of six major monocular depth cues. By doing this we hoped to understand what cues may have caused the difference seen in the first experiment as well as hopefully giving us an insight into how to make a more optimal stimulus. The results of the experiment were similar to the first with observers showing similar effects. The main difference between experiments 1 and 2 was the fact that we did find a significant main effect of stimulus for perceived amount of 3D. The most likely reason for this is that in the first experiment the stimuli were much more complicated and had multiple monocular depth cues. However, as seen in Figure 7 the results are not that clear.

For the future we plan on investigating several issues. First of all we are attempting to develop an objective metric that will measure how much 3D is in the image. This idea is best shown in Figures 1 and 6 in which there are in some images more doubling (due to the left and right images) than in others. Perhaps this may correlate with perceived quantity and quality of 3D. Secondly, we wish to look at the effect of overall image complexity as well as image size. It may be the case that a more complex image may give rise to more subjective judgments of 3D. Finally, to look at the effect of size we hope to see if smaller or larger stimuli are more or less affected by off-axis viewing. In doing so we hope to be able to better understand how to develop stimuli that make the best use of autostereoscopic systems.

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REFERENCES

1. Woodgate, G. J., Harrold, J., Jacobs, A. M. S., Moseley, R. R., & Ezra, D. "Flat panel autostereoscopic displays – characterisation and enhancement", *Proceedings of SPIE: Stereoscopic Displays and Virtual Reality Systems VII,* Merritt, J.O., Benton, S.A., Woods, A.J., and Bolas, M.T., (eds.) Vol. 3957, pp. 153-164, SPIE, Bellingham, WA, 2000.
2. Montgomery, D.J., Woodgate, G.J., Jacobs, A., Harrold, J., & Ezra, D. "Analysis of the performance of a flat panel display system convertible between 2D and autostereoscopic 3D modes", *Proceedings of SPIE: Stereoscopic Displays and Virtual Reality Systems VIII,* Woods, A.J., Bolas, M.T., Merritt, J.O., and Benton, S.A., (eds.) Vol. 4297, pp. 148-159, SPIE, Bellingham, WA, 2001.
3. Dodgson, N.A. "Analysis of the viewing zone of multi-view autostereoscopic displays", *Proceedings of SPIE: Stereoscopic Displays and Virtual Reality Systems IX,* Woods, A.J., Merritt, J.O., Benton, S.A., and Bolas, M.T., (eds.) Vol. 4660, pp. 254-265, SPIE, Bellingham, WA, 2002.
4. Touris, T. C., Eichenlaub, J. B., & Merritt, J. O. "Autostereoscopic display technology in teleoperation applications" *Proceedings of SPIE: Telemanipulator Technology,* Das, H. (ed.) Vol. 1833, pp. 158-169, SPIE, Bellingham, WA, 1992.